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CHAPTER 14

SHEATH BONDING AND GROUNDING

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1. GENERAL

This discussion provides an overview of the reasons and methods for reducing sheath losses in large cables. While calculations are shown, all of the details are not covered as completely as are in the IEEE Guide 575 [14-1]. A very complete set of references is included in that standard. The reader is urged to obtain a copy of the latest revision of that document before designing a “single-point” grounding scheme.

The terms sheath and shield will be used interchangeably since they have the same function, problems, and solutions for the purpose of this chapter.

□ Sheath refers to a water impervious, tubular metallic component of a cable that is applied over the insulation. Examples are a lead sheath and a corrugated copper or aluminum sheath. A semiconducting layer may be used under the metal to form a very smooth interface.

□ Shield refers to the conducting component of a cable that must be grounded to confine the dielectric field to the inside of the cable. Shields are generally composed of a metallic portion and a conducting (or semiconducting) extruded layer. The metallic portion can be either tape, wires, or a tube.

The cable systems that should be considered for single-point grounding are systems with cables of 1,000 kcmils and larger and with anticipated loads of over 500 amperes. Fifty years ago, those cables were the paper insulated transmission circuits that always had lead sheaths. Technical papers of that era had titles such as “Reduction of Sheath Losses in Single-Conductor Cables” [14-2] and “Sheath Bonding Transformers” [14-3], hence the term “sheath” is the preferred word rather than “shield” for this discussion.

2. CABLE IS A TRANSFORMER

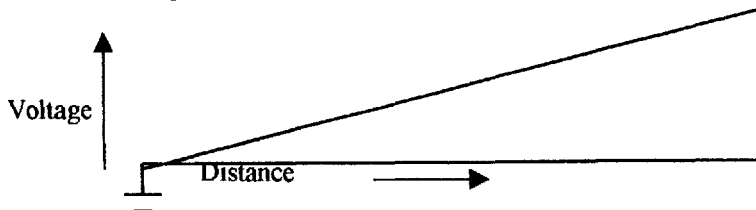
Chapter 2 described how a cable is a capacitor. That is true. Now you must think about the fact that a cable may also be a transformer.

When current flows in the “central” conductor of a cable, that current produces electromagnetic flux in the metallic shield, if present, or in any parallel conductor. This becomes a “one-turn” transformer when the shield is grounded two or more times since a circuit is formed and current flows.

We first will consider a single, shielded cable:

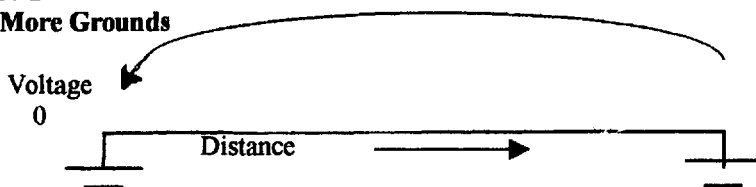
□ If the shield is only grounded one time and a circuit is not completed, the magnetic flux produces a voltage in the shield. The amount of voltage is proportional to the current in the conductor and increases as the distance from the ground increases. See Figure 14-1.

Figure 14-1
Single Point Grounding



□ If the shield is grounded two or more times or otherwise completes a circuit, the magnetic flux produces a current flow in the shield. The amount of current in the shield is inversely proportional to the resistance of the shield. (Another way of saying this is the current in the shield increases as the amount of metal in the shield increases.) The voltage stays at zero. See Figure 14-2.

Figure 14-2
Two or More Grounds



One other important concept regarding multiple grounds is that the distance between the grounds has no effect on the magnitude of the current. If the grounds are one foot apart or 1,000 feet apart, the current is the same -- depending on the current in the central conductor and the resistance of the shield. In the case of multiple cables, the spatial relationship of the cables is also a factor.

3. AMPACITY

3.1 Ampacity

In Chapter 13, there is a complete description of ampacity and the many sources of heat in a cable such as conductor, insulation, shields, etc. This heat must be carried through conduits, air, concrete, surrounding soil, and finally to ambient earth. If the heat generation in any segment is decreased, such as in the sheath, then the entire cable will have a greater ability to carry useful current.

The heat source from the shield system is the one that we will concentrate on in this discussion as we try to reduce or eliminate it.

3.2 Shield Losses

When an ac current flows in the conductor of a single-conductor cable, a magnetic field is produced. If a second conductor is within that magnetic field, a voltage that varies with the field will be introduced in that second conductor -- in our case, the sheath. See 13.3.6 for a more complete discussion of this condition.

If that second conductor is part of a circuit (connected to ground in two or more places), the induced voltage will cause a current to flow. That current generates losses that appear as heat. The heat must be dissipated the same as the other losses. Only so much heat can be dissipated for a given set of conditions, so these shield losses reduce the amount of heat that can be assigned to the phase conductor.

Let us assume that we are going to ground the shield at least two times in a run

of cable. What is the effect of the amount of metal in the shield?

The following curves present an interesting picture of the shield losses for varying amounts of metal in the shield. These curves are taken from ICEA document P 53-426 [14-5]. As you can see, they were concerned about underground residential distribution (URD) cables where the ratio of conductivity of the shield was given as a ratio of the conductivity of the main conductor. Hence one-third neutral, etc.

In the situation where 2000 kcmil aluminum conductors are triangularly spaced 7.5 inches apart, the shield loss for a one-third neutral is 1.8 times the conductor loss!

For single-conductor transmission cables having robust shields, losses such as these are likely to be encountered in multi-point grounding situations and generally are not acceptable.

3.3 Shield Capacity

The shield, or sheath, of a cable must have sufficient conductivity in metal to carry the available fault current that may be imposed on the cable. Single conductor cables should have enough metal in its shield to clear a phase-to-ground fault and with the type of reclosing scheme that will be used. It is not wise to depend on the shield of the other two phases since they may be some inches away. You need to determine:

- ❑ What is the fault current that will flow along the shield?
- ❑ What is the time involved for the back-up device to operate?
- ❑ Will the circuit be reclosed and how many times?

Too much metal in the shield of a cable section with two or more grounds is not a good idea. It costs additional money to buy such a cable and the losses not only reduce the ampacity of the cable but cause undue economic losses from the heat produced.

One way that you can test your concept of a sufficient amount of shield is to look at the performance of the cables that you have in service. Even if the present cable has a lead sheath, you can translate that amount of lead to copper equivalent. You will also need to consider what the fault current may be in the future. EPRI has developed a program that does the laborious part of the calculations [14-6].

We can “convert” metals used in sheaths or shields to copper equivalent by measuring the area of the shield metal and then translate that area to copper equivalent using the ratio of their electrical resistivities.

Table 14-1
Electrical Resistivity of Metals

Metal	Electrical Resistivity in Ohm-mm²/m x 10⁻⁸, 20 °C
Copper, annealed	1.724
Aluminum	2.83
Bronze	4.66
Lead	22.0
Iron, hard steel	24.0

As an example, we have a 138 kV LPOF cable that has a diameter of 3.00 inches over the lead and the lead is 100 mils thick.

The area of a 3.00 inch circle is: $= 7.0686 \text{ in}^2$.

The area of a circle that is under the lead is:

Diameter = 3.00-0.100-0.100 $= 2.80 \text{ in.}$

Area $= 1.4 \times 1.4 \times \pi = 6.1575 \text{ in}^2$.

Area of the lead is $7.0686 - 6.1575 = 0.9111 \text{ in}^2$.

The ratio of resistivities is $1.724 / 22.0 = 0.0784$

The copper equivalent is $0.9111 \text{ in}^2 \times 0.0784 = 0.07139 \text{ in}^2$.

To convert to cmils, multiply in^2 by $4 / \pi \times 10^6 = 90,884 \text{ cmils}$

This lead sheath is between a #1/0 AWG (105,600 cmils) and a #1 AWG (83,690 cmils).

If the sheath increases to 140 mils and the core stays the same, we have:

The area of the sheath is $= 7.4506 \text{ in}^2$.

The area of lead is $7.4506 - 6.1575 = 1.2931 \text{ in}^2$.

Multiply by the same ratio of 0.0784 = 0.1014

To convert to cmils, multiply by $4/\pi \times 10^6$ = 129,106 cmils

This is almost a #2/0 AWG (133,100 cmil) copper conductor.

Using the same concept, one can change from aluminum to copper, etc.

The allowable short-circuit currents for insulated copper conductors may be determined by the following formula:

$$[I/A]^2 t = 0.0297 \log_{10}[T_2 + 234 / T_1 + 234] \quad (14.1)$$

where

I	=	Short circuit current in amperes
A	=	Conductor area in circular mils
t	=	Time of short circuit in seconds
T_1	=	Operating temperature, 90 °C
T_2	=	Maximum short circuit temperature, 250 °C

A well-established plot of current versus time is included in [13-13]. It is important to be aware that these results are somewhat pessimistic since the heat sink of coverings is ignored and has not been addressed in equation (14.1). On the other hand, the answers given are very safe values.

3.4 Jumper Capacity

You must make a good connection between the bonding jumper and the cable sheath to have enough capacity to take the fault current to ground or to the adjacent section—no matter how well you designed the cable sheath. This is frequently a weak point in the total design.

The bonding jumper should always be larger than the equivalent sheath area and should be as short and straight as possible to reduce the impedance of that portion of the circuit. In all cases, the bonding jumper should be covered, such as with a 600 volt cable.

4. MULTIPLE POINT GROUNDING

4.1 Advantages

- No sheath isolation joints
- No voltage on the shield
- No periodic testing is needed
- No concerns when looking for faults

4.2 Disadvantages

- Lower ampacity
- Higher losses

4.3 Discussion

Although you may have already decided to drop this concept, you should be aware of the consequences of a second ground or connection appearing on a run of cable that had not been planned. Such a second ground can complete a circuit and result in very high sheath currents that could lead to a failure of all of the cable that has been subjected to those currents. The higher the calculated voltage on the sheath, the greater the current flow may be in the event of the second ground. Periodic maintenance of single-point grounded circuits should be considered. If this is will be done, a graphite layer over the jacket will enable the electrical testing of the integrity of the jacket.

5. SINGLE-POINT AND CROSS-BONDING

To be precise, single-point grounding means only one ground per phase, as will be explained later. Cross-bonding also limits sheath voltages and demonstrates the same advantages and disadvantages as single-point grounding.

5.1 Advantages

- Higher ampacity
- Lower losses

5.2 Disadvantages

- Sheath isolation joints are required
- Voltage on sheath / safety concerns

5.3 Background

The term used to describe single-point grounding from the 1920s to the 1950s was *open-circuit sheath*. The concern was to limit the *induced sheath voltage* on the cable shield. A 1950 handbook said that "The safe value of sheath voltage above ground is generally taken at 12 volts ac to eliminate or reduce electrolysis and corrosion troubles." The vast majority of the cables in those days did not have any jacket—just bare lead sheaths. Corrosion was obviously a valid concern. (Some cable manufacturers in the United States still recommend 25 volts as the maximum for most situations.) The vastly superior jacketing

materials that are available today have helped change the presently accepted value of “standing voltage” to 100 to 400 volts for normal load conditions. Since the fault currents are much higher than the load currents, it is usually considered that the shield voltage during fault conditions be kept to a few thousand volts. This is controlled by using sheath voltage limiters -- a type of surge arrester.

5.4 Single Point Bonding Methods

There are numerous methods of managing the voltage on the shields of cables with single point grounding. All have one thing in common: the need for a sheath or shield isolation joint.

Five general methods will be explored:

- ◆ Single-Point Grounding
- Cross-Bonding
- ◆ Continuous Cross-Bonding
- ◆ Auxiliary Bonding
- ◆ Series Impedance or Transformer Bonding

Diagrams of each method of connection, with a profile of the voltages that would be encountered under normal operation, are shown below.

Figure 14-3
Single-Point Grounding

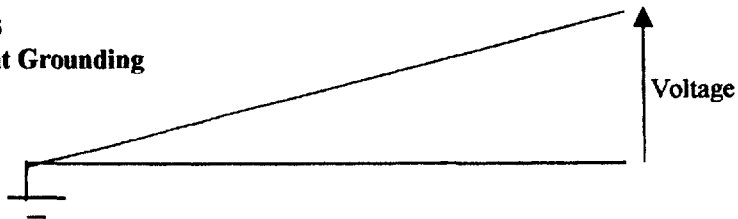
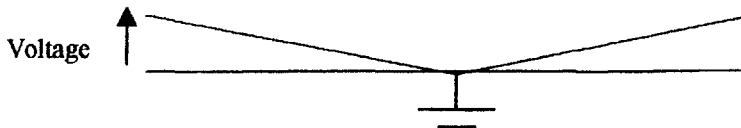


Figure 14-4
Single-Point Grounding near Center of Cable Run



In this situation, only half of the previous voltage appears on the sheath.

Figure 14-5
Cross-Bonding Connections

Legend:  Sheath Isolation
  Continuous Sheath

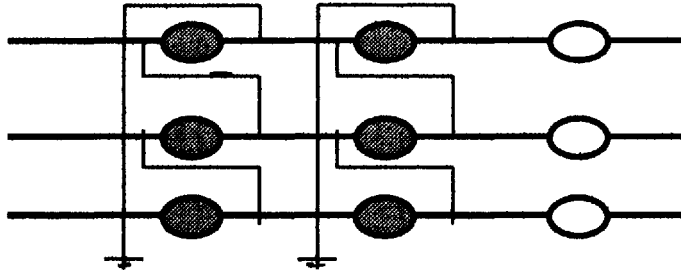


Figure 14-6
Continuous Cross-Bonding Connections

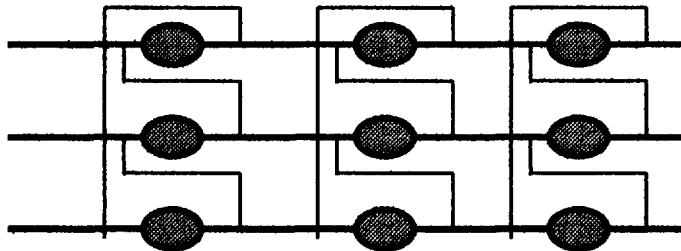
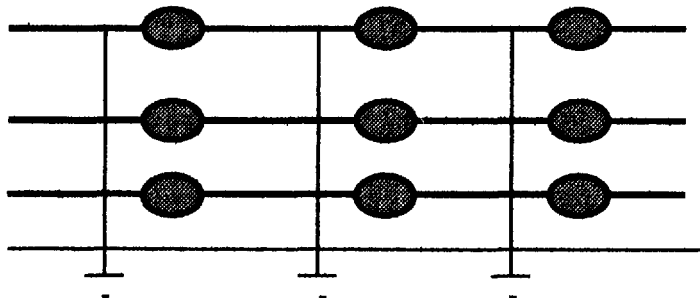


Figure 14-7
Auxiliary Cable Bonding



There are other types of grounding schemes that are possible and are in service. Generally they make use of special transformers or impedances in the ground leads that reduce the current because of the additional impedance in those leads. These were very necessary years ago when the jackets of the cables did not have the high electrical resistance and stability that are available today.

5.5 Induced Sheath Voltage Levels

Formulas for calculating shield voltages and current and losses for single conductor cables were originally developed by K. W. Miller in the 1920s [14-2]. The same general equations are also given in several handbooks. The table from reference [14-6] is included as Figure 14-7. The difference in these equations is the use of the "j" term -- to denote phase relationship -- so only the magnitude of the voltage (or current) is determined. Each case that follows will include the formulas from that reference [14-6].

The induced voltage in the sheath of one cable or for all cables in a circuit where the cables are installed as an equilateral triangle is given by:

$$V_{sh} = I \times X_m \quad (14.2)$$

where

V_{sh}	= sheath voltage in microvolts per foot of cable
I	= current in a phase conductor in amperes
X_m	= mutual inductance between conductor and sheath

The mutual inductance for a 60 hertz circuit may be determined from the formula:

$$X_m = 52.92 \log_{10} S / r_m \quad (14.3)$$

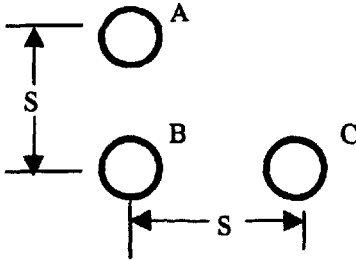
where

X_m	= mutual inductance in micro-ohms per foot
S	= cable spacing in inches
r_m	= mean radius of the shield in inches. This is the distance from the center of the conductor to the mid-point of the sheath or shield.

For the more commonly encountered cable arrangements such as a three-phase circuit, other factors must be brought into the equations. Also, A and C phases have one voltage while B phase has a different voltage. This assumes equal current in all phases and a phase rotation of A, B, and C.

Right-angle or “rectangular” spacing is a probable configuration for large, single-conductor cables in a duct bank. One arrangement is:

Figure 14-8
Right Angle Arrangement



The induced shield voltages in A and C phases are:

$$V_{sh} = I/2 \sqrt{3 Y^2 + (X_m - A/2)^2} \times 10^{-6} \quad (14.4)$$

where

V_{sh} = sheath voltage on A and C phases in volts to neutral per foot

I = current in phases conductor in amperes

Y = $X_m + A/2$

X_m = $52.92 \log_{10} S / r_m$ for 60 hertz operation

S = spacing in inches

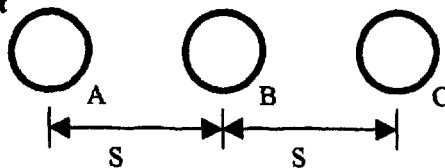
A = 15.93 micro-ohms per foot for 60 hertz operation

The induced shield voltage in B phase is:

$$V_{sh} = I \times X_m \times 10^{-6} \quad (14.5)$$

A flat configuration is commonly used for cables in a trench, but this could be a duct bank arrangement as well.

Figure 14-11
Flat Arrangement



The induced shield voltages in A and C phases are:

$$V_{sh} = I / 2 \sqrt{3 Y^2 + (X_m - A)^2} \times 10^{-6} \quad (14.6)$$

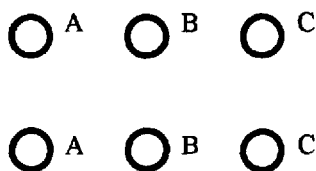
where

- V_{sh} = sheath voltage on A and C phases in volts to neutral per foot
- I = current in phases conductor in amperes
- Y = $X_m + A$ {This factor has changed from 14.4)!!!}
- X_m = $52.92 \log_{10} S / r_m$ for 60 hertz operation
- S = spacing in inches
- A = 15.93 micro-ohms per foot for 60 hertz operation

The induced shield voltage in B phase is the same as equation 14.5:

$$V_{sh} = I \times X_m \times 10^{-6} \quad (14.7)$$

Figure 14-10
Two Circuits, Flat Configuration



The induced shield voltages in phases A and C are:

$$V_{sh} = I / 2 \sqrt{3 Y^2 + (X_m - B / 2)^2} \times 10^{-6} \quad (14.8)$$

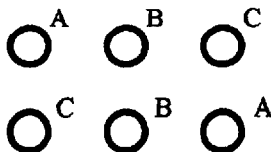
where

- V_{sh} = sheath voltage on A and C phases in volts to neutral per foot
- I = current in phase conductors in amperes
- Y = $X_m + A + B / 2$ {This factor has changed again!!!}
- X_m = $52.92 \log_{10} S / r_m$ for 60 hertz operation
- S = spacing in inches
- A = 15.93 micro-ohms per foot for 60 hertz operation
- B = 36.99 micro-ohms per foot for 60 hertz operation

The induced shield voltage for B phase is:

$$V_{sh} = I (X_m + A / 2) \times 10^{-6} \quad (14.9)$$

Figure 14-11
Two Circuits, Flat Configuration, Phases Opposite



The induced shield voltages in phases A and C are similar to equation (14.7), but Y changes:

$$V_{sh} = I / 2 \sqrt{3 Y^2 + (X_m - B / 2)^2} \times 10^{-6} \quad (14.10)$$

where

V_{sh} = sheath voltage on A and C phases in volts to neutral per foot

I = current in phases conductor in amperes

Y = $X_m + A - B / 2$ {Now a minus, not +}

X_m = $52.92 \log_{10} S / r_m$ for 60 hertz operation

S = spacing in inches

A = 15.93 micro-ohms per foot for 60 hertz operation

B = 36.99 micro-ohms per foot for 60 hertz operation

The induced voltage on B phase uses the same equation as (14.9):

$$V_{sh} = I (X_m + A / 2) \times 10^{-6} \quad (14.11)$$

5.6 Discussion of Bonding Methods

5.6.1 Cross-Bonding. The goal of any shield isolation system is to reduce induced shield currents to the point that they will not seriously affect ampacity of the circuit and to limit the voltage to a safe value.

The most commonly used is cross bonding where the cable circuit is divided into three equal sections (or six, or nine, etc.). The shield is solidly grounded at the beginning of the first section and at the end of the third section. The second section is isolated by means of shield “breaks” from the first and third sections and has its sheath bonded to other phases. See Figure 14-5.

The induced shield voltage from A phase is “cross-bonded” to B phase, etc. This phase change reduces the resultant sheath voltage, and so on, for all sections of

the circuit.

Bonding conductors must have sufficient capacity to carry the fault current that will be imposed and voltage resistance to keep the bonding jumper from being inadvertently grounded.

This method has the disadvantage of needing the joints evenly spaced through each triple section. When the joints are not evenly spaced, the voltage from one phase does not completely cancel out the other phase. This may not be critical, but it does mean that somewhat higher voltage levels will result.

5.6.2 Continuous Cross-Bonding. This is basically the same as the cross bonding of Figure 14-5 except that all of the joints have shield isolation provisions. Such a scheme is useful in situations where the triple sections are not practical from a field standpoint, such as for four sets of joints -- where the matched sets of three are not attainable.

The sheath voltages are approximately the same as for cross-bonded circuits. A disadvantage of this system is that there are no solid grounds except at the terminations.

5.6.3 Auxiliary Cable Bonding. This system is similar to the continuous cross-bonding method since all the joints must have shield isolation and all shields are bonded at each splice. The unique part of this arrangement is that the shields are connected to each other and to a separate neutral cable that runs the length of the circuit.

This permits the through fault current to be transmitted both on the shield as well as the parallel neutral cable. A reduction in the amount of shield materials is thus possible. A cable fault must still be cleared by having the fault current of that phase taken to ground at a remote point. This means that you must still put on a sufficient amount of shield metal to permit the breaker, or other back-up device, to "see" the fault.

5.6.4 Continuous Cross-Bonding, Star Ground. This system and other impedance type systems have been included in this discussion since they have been employed over the years. The basic need for these systems was to keep the sheath voltage down to that very low value of 12 volts. Now that 100+ volts is considered safe and reliable, the complications of these systems does not seem to be worthwhile. The equipment needed to accomplish these hookups are not very easy to find, have not been too reliable, and take up room in a manhole that is at a premium. Another concern is that these devices require additional maintenance time to be certain that they remain operational.

6. REFERENCES

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- [14-5] *IEEE Standard Power Cable Ampacities*, IEEE 835-1994.
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